Delineating Anomalous Mantle in the Western Superior Province

Andrew W. Frederiksen*
Department of Geological Sciences, University of Manitoba, Winnipeg, MB, Canada
frederik@cc.umanitoba.ca

and

Dave Toni
Department of Geological Sciences, University of Manitoba, Winnipeg, MB, Canada

Introduction

North America contains two crustal provinces which have been stable since Archean time: the Slave and Superior provinces (Hoffman, 1988). The Superior craton is the largest stable Archean region in the world. Its internal structure is complex, consisting of a series of subprovinces believed to represent accreted terranes (Card and Poulsen, 1998); in the western portion of the Superior, these subprovinces form narrow east-west belts that young southwards, the craton having stabilized ca. 2.6 Ga. The western Superior province is bounded to the northwest by the Trans-Hudson Orogen (stable ca. 1.6 Ga) and to the south by the Mid-Continent Rift, active ca. 1.1 Ga. The mantle lithosphere beneath stable Archean regions is widely believed to be of comparable age to the crust (see e.g. Jordan, 1978). We would therefore expect the Superior lithosphere to be of great antiquity, and to record a history of orogenic and rifting events.

The western Superior Province has been known for some time (see e.g. Silver and Kaneshima, 1993 and Kay et al., 1999) to have an unusual mantle signature, with very strong seismic anisotropy, though seismic instrumentation of the region was until recently limited to brief temporary deployments and a few permanent stations. The FedNor/POLARIS project (Darbyshire et al., 2006) provided sparse but regular coverage of western Ontario, and contributed to a combined data set (Frederiksen et al., 2007) that imaged a major boundary in mantle velocity and fabric between the eastern and western portions of the Superior Province at about 88 degrees W. The combined impact of these studies is that the western Superior is the locus of an unusual lithospheric mantle: high in P velocity, strongly anisotropic, with a consistent WSW-ESE fabric. The western and southern extent of the anomalous mantle was not well constrained due to lack of instrumentation.

A set of six instruments was installed in Manitoba in 2006 and 2007 by staff and students of the University of Manitoba, forming the University of Manitoba Teleseismic Array. Instruments were installed in Gillam (GLUM), near Pipe Pit (PPUM), in Jenpeg (JPUM), in Brandon (BRUM), in Winnipeg on the University of Manitoba Campus (UMUM), and in Star Lake (SLUM). Sites were secured through the cooperation of Manitoba Hydro, Vale Inco, and Agriculture Canada. The locations of these stations is shown in figure 1.

The region of the United States bordering on the western Superior Province has been poorly instrumented by seismometers until recently. Four stations have been installed in the area in recent years: AGMN (Agassiz National Wildlife Refuge, Minnesota), COWI (Conover, Wisconsin), and GLMI (Grayling, Michigan) in 2006, and SPMN (St.-Croix, Minnesota) in 2008. Station SPMN is part of the USArray Transportable Array, while the others lie within the US National Seismic Network. We have obtained data from these stations through the IRIS repository, and combined them with data from the University of Manitoba network in order to extend data coverage off of the western and southern edges of the Superior Province.

Method and Results

We subjected data from both US and Manitoba stations to shear-wave splitting analysis using SKS and SKKS waves. Shear-wave splitting has become a standard method in lithospheric seismology (see e.g. Silver and Chan, 1991). The specific methodology we use is described in Frederiksen et al. (2007). The result of the analysis is two numbers: the fast direction (representing the direction of the dominant upper-mantle fabric beneath the station, under the assumption that the splitting is due to aligned olivine crystals) and the split time (a measure of the total effective fabric beneath the station, i.e. a combination of the strength of the fabric and the thickness of the coherently-aligned region). Results are plotted in figure 1.

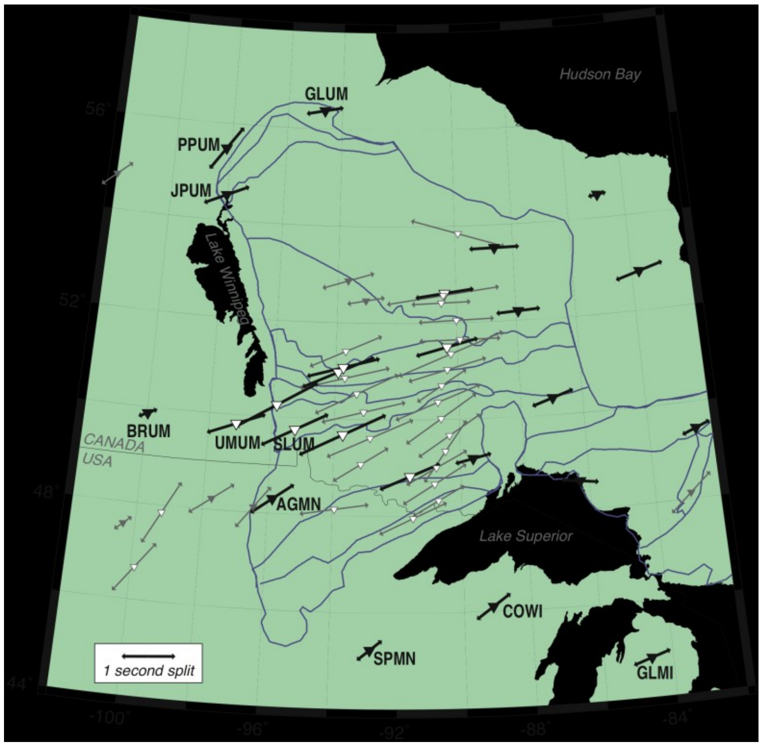

Figure 1: Shear-wave splitting results for the western Superior province. White triangles indicate split times of 1.1 s or greater. Results for named stations have not previously been published. Black lines and large triangles indicate measurements taken with a consistent methodology (unlabelled stations are from Frederiksen et al., 2007). Grey lines and smaller triangles are from previous studies (see Frederiksen et al., 2007 for references). Blue lines indicate subprovinces of the Superior Province (Card and Poulsen, 1998).

Figure 1 includes results from this study (dark arrows with labelled stations), the Frederiksen et al. (2007) compilation performed with identical methodology (dark unlabelled arrows), and previous studies (grey arrows). In the western Superior, the fast axes are closely aligned with the boundaries between tectonic subprovinces (blue lines), and the split times are uniformly high (white triangles indicate split times greater than 1.1 s).

Discussion

The geographic pattern revealed by shear-wave splitting around the western Superior is easier to see in a contour map (figure 2). The split time contour lines of 1.2 s or greater close around the western Superior (left panel), clearly delineating a zone of strongly-anisotropic mantle. Though resolution is limited by the station spacing, it is fairly clear that the anomalous region is truncated by the Mid-Continent Rift (which curves through Lake Superior) to the south and somewhere in the vicinity of the Superior-Trans Hudson Boundary to the west. However, the small split time at station BRUM (which shows indications of a multi-layered response in the raw data) complicates matters; BRUM is somewhat east of the inferred Superior-Trans Hudson boundary beneath the sedimentary cover of the Western Canada Sedimentary Basin. In combination with the previously-observed change in split time between the eastern and western Superior, the BRUM result suggests that the anomalous mantle has boundaries not corresponding to those of the Superior craton itself.

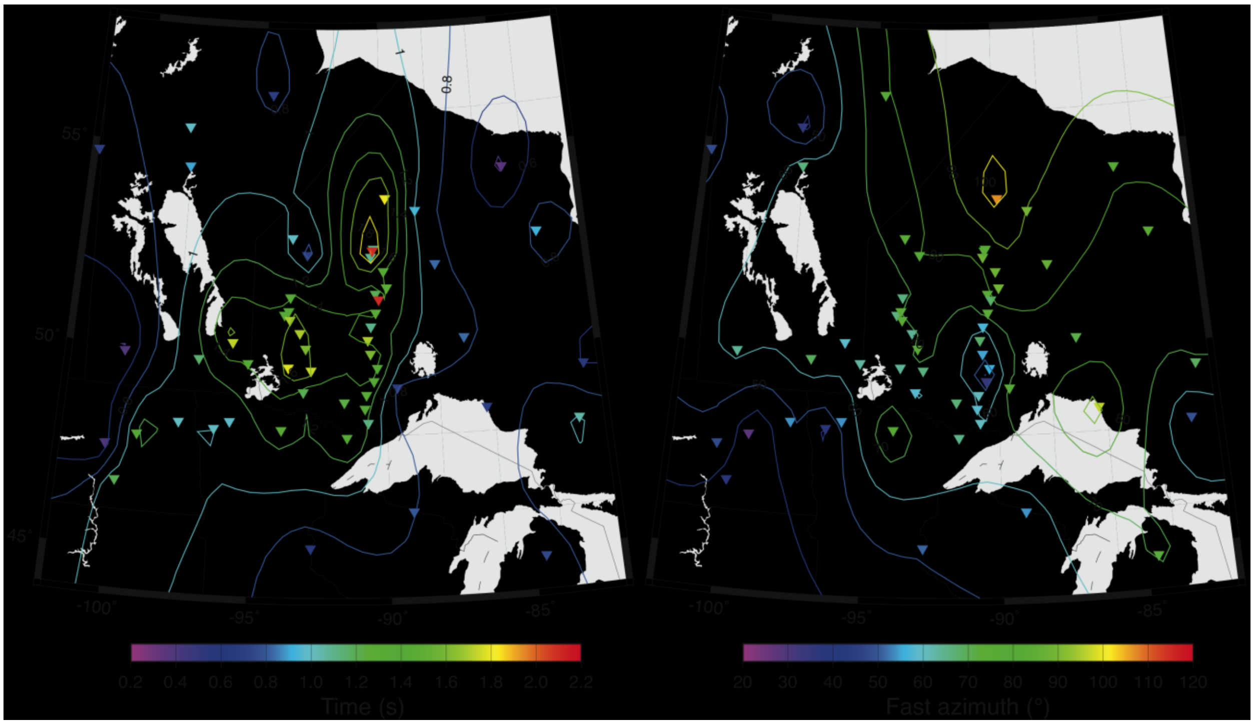

Figure 2: Contoured split times (left) and fast axes (right) for the western Superior region. Individual station measurements are plotted as coloured triangles.

Contours of the fast direction (right panel) provide some further constraints. The fast direction is close to both the grain of western Superior tectonics (figure 1) and the direction of absolute plate motion (APM) (ca. 238°, equivalent to a fast azimuth of 58°, using model HS2-NUVEL1; Gripp and Gordon, 1990). However, the evolution from NNE-SSW to E-W across the map does not match any corresponding change in the APM direction, which varies less than 5° across the map. The variations we are seeing may be influenced by APM (and hence by the asthenosphere), but require a major lithospheric component.

Comparing the high-split region to the high-velocity region located by tomography (Frederiksen et al., 2007), the correspondence is very close (figure 3). We believe both the high velocity and the strong splits to be indicators of the same anomalous mantle body, which we have now found to be truncated at the mid-continent rift as well as slightly inboard of the Superior/Trans-Hudson boundary. The origin of the anomalous body remains elusive, though it is likely to be as old as the Western Superior crust. Its truncation by the Mid-Continent Rift requires it to be, at the very least, older than the rift (1.1 Ga).

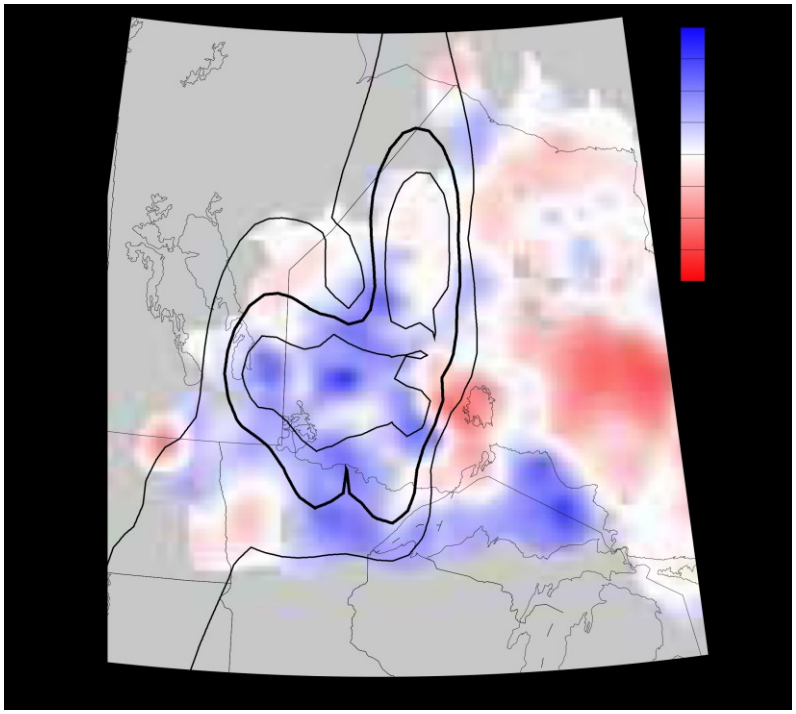

Figure 3: The 1.0, 1.2 and 1.4-second split time contours from figure 2 are overlain on a depth slice taken at 200 km through the P-wave tomography model of Frederiksen et al. (2007).

Conclusions

The Western Superior Province overlies a unique and somewhat enigmatic lithospheric body, distinct in both seismic velocity and fabric from the mantle around it. We have further delineated the edges of this body by combining data from new Canadian and American instruments; the arrival of the USArray Transportable Array in Minnesota and Wisconsin will refine the boundaries further. Understanding the origin of this unusual feature will require a more detailed examination of its internal structure, which we are beginning to attempt (see Olaleye and Frederiksen, this session).

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